SuperPower 2G HTS Wire for Demanding Electric Power Applications

Traute F. Lehner
Sr. Director of Marketing & Govt Affairs, SuperPower Inc.

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Focus of discussion

• HTS Market
  – Market sizing
  – Adoption factors

• Critical Success Factors for market adoption
  – Price
  – Technology
  – Demonstrations
  – Manufacturing
HTS market sizing model & analysis

**Definitions**

**Sizing**

**Drivers-Metrics**

**Trends**

**Conventional Markets**
- Replacing Technology Aggregate Estimate $150 to $250 Billion

**Emerging Markets**
- New Technology Aggregate Estimate $50 to $100 Billion

**Segments:**
- Energy/Utility
- Industrial
- Science-R&D

**Devices:**
- Cable
- Generators
- Transformers
- FCL
- Motors
- MRI - High field magnets
- etc.

**HTS Addressable**
- 1 to 10%
- Driven by Adoption Rate

**Market Sizing**
- Conventional 1-5%
- Emerging 5-10%

**Combined Conventional & Emerging Markets**
- Addressable Market Size — HTS Devices/Products
  - Low $4.0 to $7.5 Billion ⇔ High $12.5 to 22.5 Billion

**Market Development**
- 2010: ~1%
- 2015: ~10%
- 2020: ~25%
- 2030: ~90%

**Timeline-Adoption Rate**
- 2010: ~1%
- 2015: ~10%
- 2020: ~25%
- 2030: ~90%
HTS device portfolio - What are the winning devices?

<table>
<thead>
<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable (ac, dc)</td>
<td>• Motors, propulsion</td>
<td>• Maglev</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td>• HF magnets</td>
</tr>
<tr>
<td>FCL</td>
<td>• Cable, degaussing</td>
<td>• Motors, Marine propulsion</td>
<td>• Motors, industrial</td>
<td>• MRI</td>
<td>• Space exploration</td>
</tr>
<tr>
<td>Generators</td>
<td>• Directed energy weapons</td>
<td>• Rail engines</td>
<td>• Generators</td>
<td>• NMR</td>
<td>• SQUIDS</td>
</tr>
<tr>
<td>– Wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• High energy physics</td>
</tr>
<tr>
<td>– Utility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Electronics</td>
</tr>
<tr>
<td>– Hydro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Cell tower base station</td>
</tr>
<tr>
<td>Transformers, incl. FCL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>filters</td>
</tr>
<tr>
<td>Storage</td>
<td>• SMES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– SMES</td>
<td>• Flywheels (Bearings)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Key:
- Near-Term addressable by 2G HTS - 1-5 years
- Government interest/funding - Mid-Term 3-7 years
- Longer term/other - 5-10 years
SuperPower’s assessment of HTS wire market

• Today - **Cable** is the only market that could consume 100% of available capacity
  – High volume required, Limited performance attributes required, Price sensitive
  – Significant capital investment required to meet volume

• **AP wire** provides the greatest degree of Price/Performance attributes that create defensible position
  – Motor, Generators, SMES, Transformer, High Field Magnets, etc.
  – Continuous technology advancement to further improve barrier of defense
  – Price to customers can be achieved while profit level can be more easily maintained
  – For the near future, the wire supply will be well matched to the demand and will allow for a reasonable ROI

• **FCL Wire** – has favorable performance, price, and volume requirements, but market timing to consume 100% of capacity is questionable

• **SuperPower approach: focus on a price/performance product mix that provides:**
  – Potential contribution margins to provide pathway to profitability for all
  – Volume sufficient to load factory at capacity
  – Sales to multiple markets / applications until a clear commercial product is identified and developed
Accelerate the HTS adoption rate toward commercialization

**Technology advancement**

- **Wire**
  - Achieve competitive price
  - Increase throughput / supply
  - Meet performance parameters
- **Providing a robust product portfolio**
  - Market / device-driven
- **Continuing device demonstrations**
  - Government funding
  - Strategic partners

**Reduced business risk**

- **Price must be competitive with alternative technologies**
- **Meet or exceed customer expectations**
  - Supply
  - Quality
  - Performance
- **Provide superior customer service and support**
superior performance.

powerful technology.

Critical Market Adoption Success Factor: Price

SuperPower Inc. is a subsidiary of Royal Philips Electronics N.V.
SuperPower has a proven track record in cost-price performance on a cost in $/kA-m
Driving demand

Rapidly Decreasing 2G Wire Costs 2008-2012

Drives Demand and Production Volume
In-field performance is greatly improved

<table>
<thead>
<tr>
<th>Lift Factor of 77 K, zero field $I_c$</th>
<th>65 K 3 T</th>
<th>40 K 3 T</th>
<th>18 K 3 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undoped wire</td>
<td>0.27</td>
<td>1.02</td>
<td>2.13</td>
</tr>
<tr>
<td>Zr-doped wire</td>
<td>0.73</td>
<td>1.99</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Lift factor of Zr-doped wire is higher by

|                        | 2.7      | 1.9      | 1.6      |

At 40K and 3T, the quantity of wire required for device is reduced by $\frac{1}{2}$, greatly improving the economics of the device.
SuperPower driving Price / Performance down on two fronts: Improving manufacturing process and in-field performance

<table>
<thead>
<tr>
<th>Time</th>
<th>Performance at 77 K, zero field</th>
<th>Lift Factor at device operating condition</th>
<th>Performance at device operating condition</th>
<th>Wire price ($/m) at device operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>100-130 A</td>
<td>2</td>
<td>260 A</td>
<td>45</td>
</tr>
<tr>
<td>2 years</td>
<td>160 A</td>
<td>4</td>
<td>640 A</td>
<td>35</td>
</tr>
<tr>
<td>4 years</td>
<td>200 A</td>
<td>6</td>
<td>1200 A</td>
<td>35</td>
</tr>
</tbody>
</table>

*Improving wire performance is key to the success of our approach*
superior performance.

powerful technology.

Critical Market Adoption Success Factor:
Technology Focus - Performance Improvement Requirements

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Summary of technology development goals

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>2 yrs</th>
<th>5 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Ic at 77 K</td>
<td>100-130 A</td>
<td>200 A</td>
<td>300 A</td>
</tr>
</tbody>
</table>

* 4 mm width

Achieve higher amperage

- Improved in-field performance

![Graph showing critical current vs. angle between field and c-axis]

- Standard 2G HTS wire
- New enhanced 2G HTS wire
- Goal

- Critical current (A/4 mm)
- Angle between field and c-axis (°)

- 10x increase

Low ac loss wire

Increased production and reduced cost

- New MOCVD Reactor Design
- Silver electrodeposition

10th EPRI Superconductivity Conference • Tallahassee, FL • October 11-13, 2011
Aggressive R&D Goals Established

- Plenty of opportunities for 10x improvement in production wire performance at low temperatures & high fields → 10x lower cost/performance
- 300 A/4mm target for production wires: 3x today’s capability
- 3x additional improvement lift factor in high magnetic fields at low and intermediate temperatures by enhanced pinning schemes
- Scalable processes being developed for fully striated multi-filamentary wires in long lengths for low ac losses; ac loss reduction goal 5x (near term) to 30x
- 3x improvement in MOCVD process efficiency targeted using novel equipment engineering → 3x lower cost + 3x higher throughput
- Continued R&D for novel in-line process control and quality control for high yield manufacturing of long piece-length conductors

Superior product configurations available now…. Expect Extraordinary and Universal product in the next five years!
Planning ahead: Specialty Products Facility in Houston

- 5th MOCVD system procured by UH to be installed at SPF
- Advance R&D at UH to scale up to Manufacturing in Schenectady
- Supplement Schenectady production demand requirements
Super Power Inc.
superior performance.
powerful technology.

Critical Market Adoption Success Factor:
Application Team Focus - Demonstration Projects with Partners
Demonstration of the world’s first device with coated conductors in a live power grid

350 m cable made with 30m of 2G HTS energized in the grid
Jan. 2008 - supplied power to 25,000 households in Albany, NY

Installation at Albany Cable site (Aug. 5, 2007)
Stringent requirements for FCL being met

High critical currents over long lengths with a **tight $I_c$ bandwidth** (spec for both minimum and maximum $I_c$) to ensure uniform quench

Operating current: 2.7kA (565A continuous)
Prospective current: 63 kA peak, 25 kA rms
Limited current: <21 kA peak, <7 kA rms
ROEBEL cables made with 2,000 m of coated conductor with uniform \( I_c \) and excellent 2D \( I_c \) uniformity

\[ I_c = 341 \text{ A/12 mm}, \text{ single piece length} = 297 \text{ m} \]

**Correlation coefficient > 0.9**
Multiple coil applications using AP wire

3.6 T gantry magnet for Particle Beam Therapy. Four racetrack coils and 14 bent coils. 2,500 m with min $I_c$ of 115 A/4 mm.

Linear Induction Motor using 3 mm wide conductor to reduce ac losses

20+T HTS solenoid for muon collider

1.3 GHz NMR Magnet
8.34 T contribution from coated conductor coil

Race track coils for generator
Ultra high-field magnets demonstrated at 4.2 K with AP wire

- Je ~ 300 A/mm²
- Stress levels 300 – 400 MPa

SuperPower I.
Bmax = 26.8 T
ΔB = 7.8 T

SuperPower II.
Bmax = 27 T
ΔB = 7 T

NHMFL II.
Bmax = 35.4 T
ΔB = 4.2 T

32 T, large bore all superconducting magnet being constructed with coated conductors at NHFML
New applications possible with excellent mechanical properties & in-field performance

High current, flexible cable:
8 layers, 24 coated conductors, $I_c=130$ A

Core diameter = 5.5 mm
Cable diameter = 7.5 mm

$I_c = 2796$ A at 76 K

$I_c = 875$ A @ 4.2 K, 20 T
Current SuperPower demonstration projects

DOE Smart Grid Demonstration Program - Superconducting FCL Transformer
Waukesha – SuperPower – Oak Ridge National Laboratory

ARPA-E GRIDS Program - SMES Project

New Program – October 2011!
ARPA-E REACT Program – Low-cost wire for HTS Wind Turbine Generators
SuperPower – UH – NREL – TECO Westinghouse
superior performance.
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Critical Market Adoption Success Factor: Manufacturing Focus - Scale Up to Meet Market Demand

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Expanding manufacturing operations to meet customer demand

<table>
<thead>
<tr>
<th>Increasing annual capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improving manufacturing efficiency &amp; effectiveness:</td>
</tr>
<tr>
<td>Yield</td>
</tr>
<tr>
<td>Throughput</td>
</tr>
<tr>
<td>Quality assurance</td>
</tr>
<tr>
<td>On-time delivery</td>
</tr>
<tr>
<td>Cost improvement</td>
</tr>
<tr>
<td>Product engineering/application support</td>
</tr>
<tr>
<td>Quality certification</td>
</tr>
<tr>
<td>New product</td>
</tr>
<tr>
<td>Customer technical support</td>
</tr>
<tr>
<td>Coil design/engineering and fabrication</td>
</tr>
</tbody>
</table>
Equipment Engineering advances for testing kilometer lengths of coated conductor

- LTS wire is tested only at two ends
- Coated conductor is tested for $I_c$ and n-values **100% over entire length**

**2003:** $I_c$, n-value measurement in **1 m** intervals

**2006:** $I_c$, n-value, thickness, width measurement in **5 m** intervals

**2011:** $I_c$, n-value, thickness, width measurement in **10 m** intervals
## SuperPower Wire: Competitive Assessment

<table>
<thead>
<tr>
<th></th>
<th>SuperPower</th>
<th>Others</th>
<th>Advantage for</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance at 77 K, zero field (4 mm wide)</strong></td>
<td>100 to 160 A</td>
<td>100 A</td>
<td>SP</td>
</tr>
<tr>
<td>‘Lift Factor’ in magnetic field (at 30 K, 2 T)</td>
<td>2.6</td>
<td>1.2</td>
<td>SP</td>
</tr>
<tr>
<td>ac losses</td>
<td>Medium</td>
<td>High</td>
<td>SP</td>
</tr>
<tr>
<td>Engineering current density</td>
<td>2x</td>
<td>1x</td>
<td>SP</td>
</tr>
<tr>
<td>Strength</td>
<td>700 MPa</td>
<td>250 MPa</td>
<td>SP</td>
</tr>
<tr>
<td>Resistivity</td>
<td>High</td>
<td>Medium</td>
<td>---</td>
</tr>
<tr>
<td>“Stiffness”</td>
<td>Medium</td>
<td>High</td>
<td>---</td>
</tr>
<tr>
<td>Production volume</td>
<td>~ 300 km/yr</td>
<td>&gt;&gt; 300 km/yr</td>
<td>---</td>
</tr>
</tbody>
</table>
Large increases in coated conductor shipments and performance in last 5 years

### Table: Performance Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>2006</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $I_c$ (A/4 mm)</td>
<td>80</td>
<td>122</td>
</tr>
<tr>
<td>$I_c$ range (A/4 mm)</td>
<td>40 – 118</td>
<td>80 - 165</td>
</tr>
</tbody>
</table>

50% increase in average $I_c$, 100% increase in minimum $I_c$ and 40% increase in maximum $I_c$ achieved in 5 years of pilot manufacturing
Significant advances in manufacturing of coated conductors in the last five years

• Long lengths routinely manufactured
  – 1,000 m demonstrated with minimum Ic of ~ 300 A/cm
  – 100 – 300 m typical shipped lengths
• High critical currents in production wires
  – Critical currents of wires shipped in 2011 range from 80 to 165 A/4 mm with an average of 122 A/4mm
• Excellent in-field performance in high fields at intermediate and low temperatures
  – 800 A/cm (Je = 800 A/mm²) at 4.2 K, 10 T, field perpendicular to wire
  – 600 A/cm at 40 K, 3 T, field perpendicular to wire
• Customized to meet unique requirements of multiple applications
  – Excellent 2D uniformity of critical current across width for ROEBEL cables
  – Tight band of critical current for FCL
  – Several prototypes of cables, FCL, coils demonstrated
• Superior mechanical properties
  – Yield strength > 700 MPa with superalloy-based coated conductors
Looking ahead: SuperPower’s primary areas of focus

• Scaling up manufacturing operations to ensure supply
• Advancing the technology
• Meeting the price / performance challenge
• Providing excellent customer support
• Working closely with all stakeholders
• Collaborating to ensure success
• Participating in device demonstrations

Thank you for your interest!